The Morphology and Dynamics of Cosmic Voids

Salman Habib (T-8), Hume Feldman and Sergei Shandarin (University of Kansas), and Katrin Heitmann (ISR-1); ***habib@lanl.gov***

Cosmological observations of anisotropies in the cosmic microwave background (CMBR) and the clustering of matter have succeeded in constraining the parameters of the universe to within 10%. A consequence of this remarkable achievement is that attention can now be focused more specifically on the physics of the structure formation itself. The present understanding of the large-scale distribution of mass in the universe is based on the gravitational instability. Very small primordial fluctuations—as seen in the CMBR sky by COBE and a host of follow-up measurements—are amplified by the gravitational instability and this nonlinear process leads directly to the present distribution of galaxies and gas.

A great deal of observational effort has gone into investigating dense regions of mass, such as galaxies and galaxy clusters, because these objects are relatively easy to find. Also, carrying out large 3D sky surveys became technologically feasible only recently. With deep and wide sky coverage it is possible to probe the truly 3D topology of the universe. In this way, one obtains statistical information not only about the distribution of essentially "point" objects such as galaxies and clusters but also about the topology and geometry of the low density regions, i.e., the voids.

On scales of the order of 10 Mpc and bigger, there are two types of cosmological structures: voids and superclusters. In general, supercluster regions expand more slowly than the rest of the universe, while voids expand faster. Voids have complex substructure and isolated superclusters are possible inside voids as well as "tunnels." In contrast to the situation for dense dark matter clumps which have been extensively investigated theoretically and via simulations, theoretical models of voids remain oversimplified, e.g., by assuming spherical void shapes. However, from some high mass-resolution simulations, both voids and superclusters are known to have complicated shapes and dynamics. Despite these insights, systematic studies of how the density and dynamical environment of a void determine its mass and geometry remain to be carried out, both observationally and theoretically. On the observational side, the Sloan Digital Sky Survey areal coverage has only recently reached the point that such an exercise can be meaningfully carried out. On the theoretical side, simulations with excellent mass resolution as well as good sampling of void volumes are now possible. The work described here aims to use these simulations in consort with fast void finders and associated void diagnostics.

The mass density of voids is on the low side, ranging from a tenth to ten times the mean density of the universe. Therefore, in order to understand the structure of voids, simulations have to be geared not to high force resolution (as is necessary in high-density regions) but to high mass-resolution, in other words, the individual tracer particle masses must be small. Dark matter halos in voids need to be resolved at the level of 10^8 solar masses, thus the individual particles should have a mass of approximately 10^6 solar masses —this is a thousand times smaller than the typical mass resolution for a simulation aiming to resolve bright galaxies (10^{12} solar masses). In addition to the simulations, sophisticated diagnostic tools are needed to analyze the results. For this, we aim to employ SURFGEN, a code that constructs isodensity surfaces at many different density thresholds, identifies overdense and underdense regions, and computes four Minkowski functionals (volume, surface area, integrated mean curvature, and the Euler characteristic) for every region. In this way, one can quantitatively begin to address the morphology of voids.

Preliminary results on voids have been obtained with a set of simulations of varying sizes and numbers of particles. Voids (defined with a particular density threshold) in a box of side 128 Mpc are shown in Fig. 1. Results from these first investigations have already pointed out many of the inadequacies of

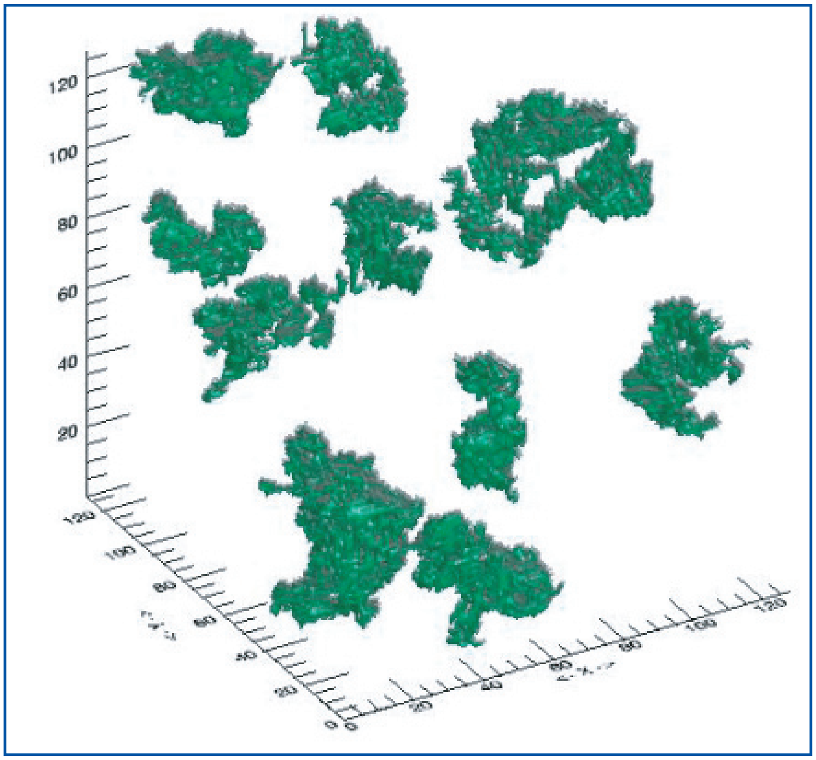

Figure 1—
Voids in a 128^3 Mpc^3 volume cosmological simulation. Two points should be noted: (i) at the density threshold used to define the voids they do not occupy a dominant volume of the simulation box; (ii) the shapes of the voids are clearly complex, both geometrically and topologically.

Figure 2—
A single void from the simulation and its best-fit ellipsoid. To provide an initial level of understanding, the evolution of voids can be investigated by studying the evolution of the corresponding ellipsoids serving as proxies for the complex underlying reality.

simple models of voids such as spheres and ellipsoids (Fig. 2). More detailed dynamical investigations with specially designed and optimized simulations will be undertaken soon. In these simulations, attention is focused on individual voids sampled at high mass resolution (very large particle number) while the rest of the simulation box is more sparsely sampled. This allows an accurate treatment of the tidal forces on the voids, yet allows them to be simulated with sufficient detail. Studies of this type will be very useful in understanding the "mini-universe" internal dynamics of voids, such as the pairwise relative velocities of void galaxies, and the dynamics and distribution (in both mass and space) of dark matter halos in voids.